Defense Technical Information Center
Compilation Part Notice

ADP010828

TITLE: Quantum Well Infrared Focal Plane Arrays for Ballistic Missile Defense and Space Applications

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Document partially illegible.

This paper is part of the following report:

TITLE: Space-Based Observation Technology

To order the complete compilation report, use: ADA391327

The following component part numbers comprise the compilation report:
ADP010816 thru ADP010842

Quantum Well Infrared Focal Plane Arrays for Ballistic Missile Defense and Space Applications

M. Z. Tidrow and W. R. Dyer
Ballistic Missile Defense Organization, BMDO/ST
7100 Defense Pentagon
Washington, DC 20301-7100
USA

Abstract

Quantum Well Infrared (IR) Photodetectors (QWIP) have been developed very quickly and demonstrated large format focal plane arrays with low noise equivalent irradiance, high uniformity, and high operability. Using the high quality GaAs material systems, QWIPs have the potential for high production yield, low cost and low power consumption. Infrared focal plane arrays (FPAs) are widely used in ballistic missile defense (BMD) for surveillance, target detection, target tracking, and discrimination. These functions are performed from satellites, aircraft platforms, fixed locations or interceptors. Some ballistic missile defense sensor functions can be performed with single-color FPAs, while others require simultaneous measurements in two to four IR bands. The temperatures of most advanced BMD targets require FPA wavelengths in the mid-wave IR (MWIR), long-wave IR (LWIR), or very-long-wave IR (VLWIR) bands. Important FPA characteristics for future BMD FPAs will include large format, high sensitivity, low 1/f noise, good uniformity, and high operability. Due to the colder environment in space applications, VLWIR is very important for sensor design. QWIPs have lower sensitivity than mercury cadmium telluride FPAs at MWIR and LWIR wavelengths, but QWIP's performance at low temperature and very-long-wave IR makes it especially attractive for IR space systems. In addition, multicolor VLWIR sensing is important to eliminate the effects of earthshine in exoatmospheric discrimination. Superior multicolor capability has been demonstrated in QWIP manufacture. In this paper, an overview of the state-of-the-art of IR sensors will be given, and the advantages and shortfalls of QWIPs for BMD and space-based applications will be discussed.

Introduction

Infrared focal plane array (IRFPA) technology is very important to ballistic missile defense and space-based applications. as well as to other military and commercial applications. The IR spectrum can be divided into short wave IR (SWIR) (1 to 3 μm), MWIR (3 to 5 μm), LWIR (8 to 12 μm), and VLWIR (>12 μm). All BMDO supported Major Defense Acquisition Programs have urgent needs for high quality IRFPAs. Ballistic Missile Defense Organization (BMDO) has two major mission areas in ballistic missile defense: National Missile Defense and Theater Missile Defense. Under these two umbrellas, BMDO has a number of programs, including Space Based IR System (-High Earth Orbit and -Low Earth Orbit), Navy Theater Wide, Navy Area Defense, Theater High Altitude Area Defense, and the Medium Extended Air Defense System.

In the functional areas, the missile defense systems are performed either in endo-atmosphere, or exo-atmosphere. Endoatmospheric interceptors and airborne surveillance sensors used for tactical applications typically observe warm targets with high background irradiance from heated windows, scattered sunlight, and the earth's surface. Such applications require accurate measurement and subtraction of background irradiance to detect the target's signal. In contrast, exoatmospheric interceptors and space based surveillance sensors used for strategic applications typically engage cool targets with low background irradiance levels. The targets are often far away and unresolved at the early stage of detection. For strategic applications where the scene is a space background and the targets are at relatively low temperatures, LWIR and VLWIR are very important wavelength bands. For tactical applications, the atmospheric transmission windows of SWIR, MWIR and LWIR determine the most important wavelength bands. Therefore, IRFPAs with high sensitivity, high uniformity, large format, and flexible wavelength are needed from SWIR to VLWIR. Multicolor capabilities are highly desirable for advance IR sensor systems. FPA stability, reproducibility, yield, cost, maintenance, and manufacturability are also very important issues.

IR Detectors and FPAs

At present time and in the near future, we expect all high performance IRFPAs for ballistic missile defense and space-based applications to be cooled IR photodetector arrays. Uncooled IR detector FPAs have been developed very quickly in recent years with large format arrays developed. They include both microbolometer and ferroelectric detector arrays. The thin film microbolometer structures directly built on Si readout circuitry are more mature than the thin film ferroelectric detector arrays at present time. Uncooled IR detector arrays have the potential to outperform cooled IR detectors at VLWIR. However, uncooled detectors developed so far are much less sensitive than the cooled detectors and require a relatively low frame rate. They

Paper presented at the RTO SET Symposium on "Space-Based Observation Technology", held on the Island of Samos, Greece, 16-18 October 2000, and published in RTO MP-61.

also have no intrinsic multicolor capability. Most commercial markets probably will be dominated by uncooled IR detector FPAs operating at room temperature, except for medical applications where high resolution and accuracy are needed. There are many commercial applications of IRFPAs, including medical, fire control, industrial quality control, environmental, surveillance, and driver's vision enhancement.

Current cooled IR sensor systems use material systems, such as InSb, PtSi, HgCdTe, and Si:As blocked impurity band detectors. The quantum well infrared photodetector is a relatively new technology to IR sensor applications. Among these cooled IR detector systems, PtSi FPAs are highly uniform and manufacturable. But they have very low quantum efficiency and can only operate in the MWIR range. InSb FPA technology is mature with very high sensitivity, but it can also only be operated in the MWIR range. Neither PtSi nor InSb has wavelength tunability or multicolor capabilities. Si:As has a wide band spectrum (0.8 to 30 μm), with no intrinsic tunability or multicolor capability, and it can only be operated at very low temperatures around 10-12 K. HgCdTe and QWIP offer high sensitivity with wavelength flexibility in MWIR, LWIR, and VLWIR regions, as well as multicolor capabilities. HgCdTe can also work at SWIR, while QWIP has to go to direct band gap scheme for SWIR. In this paper, the discussion is concentrated on QWIP technology on LWIR, VLWIR, and multicolor applications, especially those at low temperature and low background. The fundamental properties of each system and how they affect the device performance and applications are also discussed.

Multicolor FPAs

An important requirement for BMD missions is multicolor FPAs. Although many BMD functions can be accomplished using only one color, multicolor FPAs offer better performance in many cases, and some functions can be performed only with multicolor. Surveillance, target detection, and target tracking can be done using single-color FPAs if the targets are easy to identify. However, when the target and/or background are uncertain, or may change during an engagement, single-color design involves compromises that can degrade overall mission capability. Two or more spectral bands (colors) can greatly improve overall performance in such cases. For example, when a sensor must track a ballistic missile through booster burnout, much better detection and tracking will result if two colors are used—one before and one after burnout. Discrimination of targets from decoys and debris is greatly enhanced by using multicolor FPAs. While the irradiance measured by a single-color sensor is a useful discriminant, estimation of thermal characteristics requires two to four colors. The maximum number of simultaneous colors needed for future BMD missions appears to be four. It is desirable that each of the four colors be easily and quickly variable by changing a bias voltage. This will permit simultaneous measurements in four bands optimized to target detection and background rejection, which is preferable to hyperspectral FPAs with many narrow bands.

Two-Color Temperature Estimation

Ignoring optical losses and spectral filtering, the power measured by a seeker of aperture area S m^2 in wavelength band (λ_1, λ_2) meters from a gray body of emissivity ε, area A m^2, and temperature T °K, at a range of r meters is

$$P(T,\lambda_1,\lambda_2) = \varepsilon \frac{SA}{r^2} \int_{\lambda_1}^{\lambda_2} \frac{2hc^2\lambda^{-5}}{e^{\frac{ch}{\lambda kT}} - 1} d\lambda \qquad Watts \qquad [1]$$

where c=2.988x10^8 m/sec is the speed of light, h=6.625x10^{-34} J sec is Planck's constant and k=1.381x10^{-23} J/K is Boltzman's constant. It is not possible to accurately estimate the target's temperature T using only one wavelength band (λ_1, λ_2), because ε, A, r and T are all unknown. However, if measurements are made simultaneously in two wavelength bands (λ_1, λ_2), (λ_3, λ_4), their ratio R cancels ε, A, S, and r, and can be used to estimate T. The ratio R is plotted in Figure 1 for two sets of wavebands. The ratio R is a monotonic function of T, which allows T to be found uniquely for every R. Also note from Figure 1 that the slope dR/dT is larger for the more separated wavebands. Hence, temperature estimation errors will be smallest when the wavebands are separated as much as practical, consistent with maximizing signal to noise ratio in both bands.

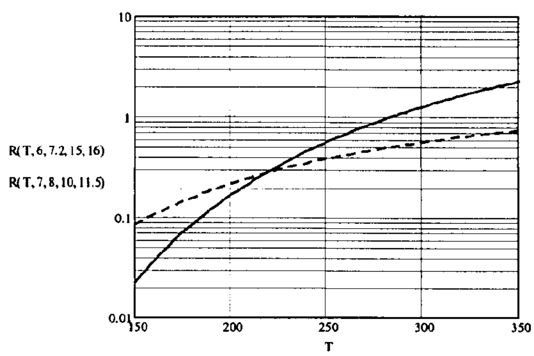

Figure 1. Ratio Of Measurements v Temperature T

Three-Color Temperature Estimation with Earthshine

While solar scattering can usually be ignored at wavelengths longer than 6 μm, temperature estimation generally will be complicated by earthshine reflected from targets at MWIR-VLWIR wavelengths. In this case, the measured irradiance is

$$P(T,\lambda_1,\lambda_2) = P_{tgt}(T,\lambda_1,\lambda_2) + \alpha P_E(\lambda_1,\lambda_2) \qquad [2]$$

where α accounts for the view factor of the reflected earthshine and the subscripts tgt and E denote IR emitted

from the target and earthshine reflected from the target respectively. Equation [2] contains three unknowns, $P_{tgt}(T, \lambda_1, \lambda_2)$, $P_E(\lambda_1, \lambda_2)$, and α, but it is also a function of ε, A, and r, because the terms have forms similar to equation [1]. To make a temperature estimate, three measurements, $P_E(\lambda_1, \lambda_2)$, $P_E(\lambda_3, \lambda_4)$, $P_E(\lambda_5, \lambda_6)$ of the target are needed. In addition, three estimates $P(T, \lambda_1, \lambda_2)$, $P(T, \lambda_3, \lambda_4)$, $P(T, \lambda_5, \lambda_6)$ are made by looking directly at the earth or by measuring the earthshine reflected from a reference sphere near the target, with the same sensor used for the target measurements. With the P_E terms estimated, multiply $P(T,\lambda_3,\lambda_4)$ by the ratio of earthshine measurements $P_E(\lambda_1,\lambda_2)/P_E(\lambda_3,\lambda_4)$ and subtract the result from $P(T,\lambda_1,\lambda_2)$. The result is

$$D(T,\lambda_1,\lambda_2,\lambda_3,\lambda_4) = P(T,\lambda_3,\lambda_4)\left[\frac{P(T,\lambda_1,\lambda_2)}{P(T,\lambda_3,\lambda_4)} - \frac{P_E(\lambda_1,\lambda_2)}{P_E(\lambda_3,\lambda_4)}\right] \qquad [3]$$

After calculating $D(T,\lambda_1,\lambda_2,\lambda_5,\lambda_6))$ the same way, form the ratio U, defined as

$$U(T,\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5,\lambda_6) = D(\lambda_1,\lambda_2,\lambda_3,\lambda_4)/D(\lambda_1,\lambda_2,\lambda_5,\lambda_6)$$

$$= \frac{P(T,\lambda_3,\lambda_4)}{P(T,\lambda_5,\lambda_6)} \times \left[\frac{\dfrac{P(T,\lambda_1,\lambda_2)}{P(T,\lambda_3,\lambda_4)} - \dfrac{P_E(\lambda_1,\lambda_2)}{P_E(\lambda_3,\lambda_4)}}{\dfrac{P(T,\lambda_1,\lambda_2)}{P(T,\lambda_5,\lambda_6)} - \dfrac{P_E(\lambda_1,\lambda_2)}{P_E(\lambda_5,\lambda_6)}}\right] \qquad [4]$$

Each term of U is a ratio of irradiance measurements, and hence is independent of ε, A, and r. Plots of U vs T are shown in Figure 2 for two sets of three bands. U is a monotonic function of T, and hence it provides a unique estimate of T for each value of U. As in the no-earthshine case, errors are reduced when the wavebands are separated as much as practical. Comparison of Figures 1 and 2 indicates that earthshine causes a reduction in the accuracy of the temperature estimates since the slopes of the dU/dT curves are smaller that those of the dR/dT curves.

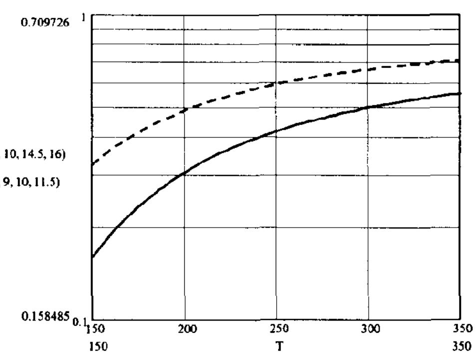

Figure 2. Ratio U vs Temperature T

Measured exoatmospheric data indicates that the accuracies of the earthshine ratio terms of [4] are maximized if one of the detector colors is chosen in a band where the earth's atmosphere partially blocks earthshine. There are three blocking bands in the MWIR-VLWIR region that can be used: the water band (5.5 μm – 7.5 μm), the ozone band (9.4 μm – 9.9 μm), and the CO_2 band (14 μm –16 μm). While none of these bands blocks earthshine totally, the CO_2 band offers the best combination of spectral width and earthshine blocking. The ozone band is narrow, and the lower portion of the water band should be avoided due to solar scattering. Best accuracy results when the color in the blocking band is between the other two colors. This makes QWIPs attractive because they can easily cover the CO_2 band and beyond.

If the targets of interest are not very reflective, it may be possible to ignore earthshine and use a two-color FPA with both colors in located separate earthshine blocking bands. The range of expected target temperatures and reflectivities determines the benefits of this approach, but it has the advantage of relative simplicity, and in some cases better accuracy. One of the blocking bands should be the CO_2 band due to its wide spectrum and good blocking characteristics. The solid curve of Figure 1 represents the potential of this method. Comparison with Figure 2 shows that the two-band approximation has larger slope and therefore may provide greater accuracy than the three-band method. After T has been estimated, target's emissivity-area product, εA, can also be estimated if an estimate of range r is available.

Four-Color Temperature Estimation of Non-gray Targets

The above two- and three-color developments assume a graybody target. If the target is non-gray (i.e., ε varies with λ), simultaneous measurements in four or more bands are needed. Spitzberg (1) has shown that graybody emissivity is coordinated well enough with wavelength that four uniformly spaced wavelength bands allow fairly good temperature estimation of non-gray targets between 5 μm and 25 μm. Best results are obtained when $\varepsilon(\lambda)$ is expanded in an orthogonal series, and more bands improve the estimates somewhat. As in the graybody case, target's emissivity-area product, εA, can also be estimated if an estimate of range is available.

Quantum Well Infrared Photodetectors and Arrays

QWIPs are semiconductor devices operating at cooled temperatures decided by the cutoff wavelength. A typical QWIP consists of GaAs/AlGaAs 30 to 50 quantum well periods (2). Using GaAs as the well region and AlGaAs as the barrier region, confined quantum well structures can be formed when the well width is small. The thickness of the GaAs layer determines the well width, and the x value in $Al_xGa_{1-x}As$ determines the barrier height. QWIP uses intersubband transitions within the quantum wells either in conduction band (n-type) or valence band (p-type). The well region has one bound ground state and one or more excited states, depending on the barrier structure. N-type QWIPs are donor doped,

resulting in a Fermi energy above the ground state. Electrons in the ground state can absorb IR photons with energy coinciding with the energy difference between the excited and ground states. Using either InGaAs or GaAs as well region, the detection wavelength of QWIPs can vary from 4 μm to larger than 20 μm. With different combinations of barriers and well structures, different detection wavelengths, detection bandwidths, and multicolor combinations can be achieved. QWIPs are usually operated in the photoconductive (PC) mode, and bias voltage (typically around 2 V) is applied to sweep the excited electron out of the well region.

QWIPs use III-V semiconductor material, mostly GaAs/AlGaAs. The advantages of the GaAs/AlGaAs material system are that it has superior bond strength and material stability, well behaved dopants, and thermal stability. Because of the maturity of GaAs technology, device processing and array fabrication for QWIPs is mature and repeatable. The outcome is highly uniform FPAs with high operability and high yield. One major disadvantage of the intersubband transition used in n-type QWIPs is that it has relatively low quantum efficiency as compared with other interband transition semiconductor devices such as HgCdTe, or InSb. Since the optical absorption is anisotropic; the absorption cross section is proportional to the square of the component of electric polarization perpendicular to the quantum well layers. This implies that a simple QWIP does not directly absorb normally incident light. Therefore, all n-type QWIP pixels for two-dimensional (2-D) arrays include a metalized diffraction grating or other similar structure to couple normally incident light into directions that are strongly absorbed by the quantum wells. The absorption quantum efficiency of the detectors is therefore a function of both the absorption strength of the quantum wells and the effectiveness of the coupling structure. Another characteristic of intersubband transition is the short carrier lifetime. A short carrier lifetime gives an intrinsically fast device speed, however, it also forces QWIP to operate at a lower temperature due to the higher dark current.

Currently, LWIR QWIP FPAs with up to 640x480 pixels have been demonstrated by Lockheed Martin (3) and JPL (4). JPL also demonstrated a 128x128 QWIP FPA at 15 μm (5). Multicolor 256 x 256 MW/LW and near infrared (NIR)/LW FPAs with sequential imaging were demonstrated by Lockheed Martin in 1993 and 1994, respectively (6). The most recent development in multicolor QWIP FPAs are two color MW/LW and LW/LW FPAs with simultaneous imaging capability at Lockheed Martin (6). The results of the LW/LW FPA have NEDT of 24 mK for the 8.6 μm and 35 mK for the 11.2 μm at 40 K with *f*/2 optics. The pixel operability in each color is >97 percent and has now improved to >99 percent.

QWIPs for BMD and Space Based Applications

Ballistic missile defense requires both tactical and strategic applications, while space based IR falls into the strategic category. In tactical applications, the scene usually has a high background (300K). The target temperature is high (>300K) and the distance is in the short to medium range. Due to the high background, the IRFPA performance is mostly background noise limited. For tactical applications, QWIP FPAs in the format of 320x256 are commercially available (Lockheed Martin) (7) QWIP is grounded on a commercial III-V material technology that is the basis of a multibillion dollar electronics industry). The substrates, MBE growth, and processing technology are very mature and a high yield can be achieved. The production of QWIP FPAs can also leverage other III-V semiconductor devices. Therefore the cost of QWIP FPAs are expected to be much lower than other cooled IRFPAs such as HgCdTe and InSb.

For space based IR systems, the scenario usually describes a very low background with far away targets. In countermeasures, the target can be cooled to a very low temperature, which gives very low IR signatures that peak in VLWIR spectrum. Therefore, VLWIR sensors are very important in strategic missile defenses and space applications. FPAs of 12 to 18 μm are very useful for the detection of cold objects such as ballistic missiles in midcourse. Using band gap engineering and mature GaAs technology, extension of tactical QWIPs to VLWIR is relatively easy because there is very little change in material properties, growth, and processing. At VLWIR, the intersubband spacing of a QWIP is relatively smaller than at LWIR. Due to the lower quantum well barriers, the dark current of thermionic emission dominates at a lower temperature. In order to achieve equivalent performance of a 10 μm cutoff QWIP at 77 K, the temperature needs to be cooled to 55 K for a 15 μm cutoff and 40 K for an 18 μm cutoff. An unoptimized 128 × 128 pixel QWIP FPA at a 15 μm cutoff wavelength has been demonstrated by JPL (5) with an NEDT of 30 mK at 45 K with 300 K background and *f*/2.3 optics. This initial array gives excellent images with 99.9 percent operability and uncorrected responsivity nonuniformity of 2.4 percent. Comparing QWIP with HgCdTe at 15 μm, QWIP has higher operability and uniformity, and higher yield.

In the situation of low background applications, the signal from the target is usually very weak due to a low irradiance and far distance of the target, besides peaking at a longer wavelength. In order to maintain the signal to noise ratio, high quantum efficiency and low noise is needed. In QWIP, thermally generated intrinsic dark current dominates the device performance at low background. The behavior of the dark current of a QWIP is well understood. It has three mechanisms with one mechanism usually dominating at one temperature range, even though all three mechanisms contribute at all

temperatures. At low temperatures ($T < 40$ K for 10 μm cutoff), the dark current is mostly caused by defect related direct tunneling (DT). With high quality III-V material growth and processing, this dark current is very small. In the medium operating temperature range (40 to 70 K for 10 μm cutoff), thermally assisted tunneling (TAT) dominates. Electrons are thermally excited and tunnel through the barriers, with possible assistance from defects in the triangle part of the barrier that forms under bias. At high temperature (>70 K for 10 μm cutoff), thermally excited electrons are thermionically emitted (TE) above the barriers. One can adjust the device structures, doping densities, and bias conditions to get optimum dark current and photoresponse for specific applications. However, when the device is TE dominated, which means the dark electrons have energy and transport mechanisms similar to photoelectrons, it is very hard to reduce the dark current without sacrificing the photoelectrons. A typical LWIR QWIP dark current density at 77 K is about 5×10^{-4} A/cm^2 for $\lambda_c = 9$ μm and bias voltage of –2V. It usually reduces exponentially with inverse temperature with a reduction of three to five orders of magnitude between 77 K and 40 K. A dark current of 5×10^{-4} A/cm^2 is in the nanoampere for a 24 × 24 μm^2 pixel. Certain techniques, such as the E-QWIP (8) and C-QWIP (9), use coupling structures that are etched right through the QW stack. These schemes can maintain the detector optical area, while reducing the dark current by a factor up to 5. The fact that this can be done without introducing significant surface currents is further evidence of the low surface leakage along the unpassivated GaAs/AlGaAs surface.

IR detectors such as HgCdTe suffer from the tunneling dark current caused by defects when detector is operated at low temperature and at very long wavelength. The outcome is high nonuniformity caused by defect related dark current. Due to the high quality materials, there is a less problem for QWIP on defect related dark current when operating at low temperature and very long wavelength. However, there are some fundamental issues related to QWIPs for low background applications. First, due to the intersubband transition properties, the dark current of QWIPs is always higher than that of interband transition detectors, such as HgCdTe when operating at the same temperature. This is a fundamental limit, not due to technology immaturity as in the HgCdTe case. QWIP's dark current depends strongly on the doping density during the device growth. Reducing the doping could reduce the dark current. However, for low background applications, lowly doped QWIPs suffer from a long response time due to the depletion of the charged quantum well. A dielectric relaxation is also observed which is not yet well understood. The low quantum efficiency and gain product of QWIP also prohibits QWIP's ability to see very dim target at a very far distance which is most of the case for space based IR systems.

Summary

In summary, QWIP FPAs are mature for tactical applications and are commercially available. QWIP FPAs have many advantages for space based applications, such as high uniformity, high operability, high yield and low cost which are very important to space based IR systems. However, there are some fundamental limitations in QWIPs, which require them to operate at a relatively lower temperature compared to HgCdTe. Current QWIP's quantum efficiency and gain product is around 2 to 6 percent, which needs significant improvement for long range detection as in space based IR system. How much the uniformity and operability could compensate for the low quantum efficiency is yet to be determined. The future applications of QWIP also depend on the speed and maturity of other IR materials system development. Quantum dot infrared photodetectors (QDIPs) is a potential replacement for QWIPs (10). QDIPs have certain advantages over QWIP. First, no quantum selection rules prevent normal incident absorption in a QDIP, removing the need for grating. Second, higher photoconductive gain could be achieved in QDIPs due to longer lifetime of excited electrons. And third, there is the added potential of higher response due to the excited electron confinement in three dimensions, which results in a larger transition probability overlap integral and higher dipole matrix elements. The dark current in a QDIP is also smaller theoretically due to the three-D confinement. Therefore, a higher sensitivity is expected in QDIP than in QWIPs. However, QDIP is still in the developing stage and the technology is not even close to ready. QDIP also has intrinsically very narrow bandwith, which might eliminate its potential of certain wideband applications.

References

(1) Spitzberg, R.M. "Parameter Estimation for Gray and Nongray Targets: Theory and Data Analyses", Optical Engineering, July 1994.

(2) Sheng S. Li and Meimei Z. Tidrow, "Quantum Well Infrared Photodetector", Chapter 9, Handbook of Nanostructured Materials and Nanotechnology, edited by H. S. Nalwa, Volume 4: Optical Properties, Academic Press, 2000.

(3) L. T. Claiborne, S. L. Barnes, A. J. Brouns, F. C. Case, E. Feltes, T. A. Shater, K. L. Brown, M. Sensiper, R. J. Martin, C. Chandler, and P. Vu, in Proc. 1996 Meeting of the IRIS Specialty Group on Infrared Detectors, 1996.

(4) S. D. Gunapala, S. V. Bandara, J. K. Liu, W. Hong, M. Sundaram, R. Carralejo, C. A. Shott, P. D. Maker, and R. E. Muller, SPIE (1997).

(5) S. D. Gunapala, J. S. Park, G. Sarusi, T. L. Lin, J. K. Liu, P. D. Maker, R. E. A. Muller, C. A. Shott, and T. Hoelter, IEEE Trans. Electron. Devices 44, 45 (1997).

(6) M. Sundaram, T. Faska, S. Wang, A. Reisinger, M. Taylor, R. Williams, K. Zabierek, R. O. D. Burrows, D. Walker, S. Wade, S. Duvall, R. Yanka, K. Nichols, A. Vera, D. Bingham, C. Cooke, J. Roussis, M. Winn, J. Ahearn, G. Milne, K. Brown, R. Martin, K. Reiff, and W. Spahr, in Proc. the IRIS Specialty Group on Infrared Detectors, Boulder, CO, 1998 (ERIM).

(7) Private conversation with Lockheed Martin

(8) M. A. Dodd, S. L. Barnes, A. J. Brouns, F. C. Case, L. T. Claiborne, and M. Z. Tidrow, in Proc. the 1997 Meeting of the IRIS Specialty Group on Infrared Detectors, , 1997.

(9) C. J. Chen, K. K. Choi, M. Z. Tidrow, and D. C. Tsui, Appl. Phys. Lett. 68, 1446 (1996).

(10) Xudong Jiang, Sheng S. Li, and M. Z. Tidrow, Physica E, 5, 27-35 (1999)